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Investigation for the enrichment pattern of the element abundances in r+s star HE 0338-3945: a special r-II star?

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ABSTRACT

The very metal-poor star HE 0338-3945 shows a double-enhanced pattern of the neutron-capture elements. The study to this sample could make people gain a better understanding of s- and r-process nucleosynthesis at low metallicity. Using a parametric model, we find that the abundance pattern of the neutron-capture elements could be best explained by a binary system formed in a molecular cloud, which had been polluted by r-process material. The observed abundance pattern of C and N can be explained by an AGB model (Karakas & Lattanzio 2007). Combing with the parameters obtained from Cui & Zhang (2006), we suggest that the initial mass of the AGB companion is most likely to be about $2.5M_\odot$, which excludes the possibility of forming a type-1.5 supernova. By comparing with the observational abundance pattern of CS 22892-052, we find that the dominating production of O should accompany with the production of the heavy r-process elements of r+s stars. Similar to r-II stars, the heavy r-process elements are not produced in conjunction with all the light elements from Na to Fe group. The abundance pattern of the light and r-process elements for HE 0338-3945 is very close to the pattern of the r-II star CS 22892-052. So, we suggest that this star HE 0338-3945 should be a special r-II star.

Subject headings: Stars: abundances - Stars: AGB and post-AGB - Stars: chemically peculiar

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1. Introduction

The two neutron-capture processes, i.e. the (slow) s-process and the (rapid) r-process, occur under different physical conditions and are therefore likely to arise in different astrophysical sites. The dominant site of the s-process is thought to be the asymptotic giant branch (AGB) phase in low- and intermediate-mass stars (Busso et al. 1999). The site or sites of the r-process are not known, although suggestions include the ν-driven wind of Type II supernovae (Woosley & Hoffman 1992; Woosley et al. 1994), the mergers of neutron stars (Lattimer & Schramm 1974; Rosswog et al. 2000), accretion-induced collapse (AIC; Qian & Wasserburg 2003), and Type 1.5 supernovae (Iben & Renzini 1983; Zijlstra 2004). The neutron-capture elements are composed of some pure r-process, some pure s-process, and some mixed-parentage isotopes. As a result, when the solar system's abundances are separated into the contributions from the s-process and the r-process, some elements are mostly contributed by the r-process, such as Eu, and some by the s-process, such as Ba. Therefore, Eu is commonly referred to as an "r-process element", and Ba as an "s-process element".

Observations for metal-poor stars with metallicities lower than [Fe/H] $= -2.5$ enriched in neutron-capture elements have revealed the solar r-process pattern, while only a few cases of highly r-process-enhanced stars (hereafter "r-II" stars; Sneden et al. 1996, 2003; Cayrel et al. 2001; Hill et al. 2002), have been noted. Despite their considerable metal deficiency, these stars seem to have experienced an r-process that barely differs from the sum of r-processes that enriched the pre-solar nebula. This has led to suggestions that r-process production may be independent of the initial metallicity of the site, especially for the heavier n-capture elements ($Z \geq 56$; Cowan et al. 1995; Sneden et al. 1996, 2000; Norris et al. 1997).

It is puzzling that several stars show enhancements of both r-process and s-process elements (r+s stars hereafter; Hill et al. 2000; Cohen et al. 2003), as they require pollution from both an AGB star and a supernova. The origin of the abundance peculiarities of the r+s stars is not clear, and many scenarios have been presented (Jonsell et al. 2006). Qian & Wasserburg (2003) proposed a scenario for the creation of r+s stars. Firstly, some s-process material is accreted from an AGB star, which turns into a white dwarf, then, during the evolution of the system, the white dwarf accretes matter from the polluted star and suffers an AIC to a neutron star. The ν-driven wind produces an r-process, which also pollutes the companion. A possible problem, as these authors mentioned, is the still uncertain nucleosynthesis in accretion-induced collapse, which may or may not produce the r-process. Another possible r+s scenario is that the AGB star transfers s-rich matter to the observed star but does not suffer a large mass loss, and at the end of the AGB phase the degenerate core of the low-metallicity, high-mass AGB star may reach the Chandrasekhar

mass, leading to a Type 1.5 supernova (Zijlstra 2004). Such suggestion can explain both the enhancement pattern and the metallicity dependence of the double-enhanced halo stars. There is another scenario of the origin for the double-enhanced halo stars. In this picture, the formation of a binary system of low-mass stars was triggered by a supernova that polluted and clumped a nearby molecular cloud. Subsequently, the observed star, which is already strongly enhanced in r-process elements, receives large amounts of s-process elements from the initially more massive star that underwent the AGB phase and turns into the double-enhanced star (Aoki et al. 2002; Delaude et al. 2004; Barbuy et al. 2005; Gallino et al. 2005; Ivans et al. 2005).

The nucleosynthesis of neutron-capture elements for CEMP (carbon-enhanced metal-poor) stars can be investigated by the abundance pattern of r+s stars. Recently, an analysis of the element abundances for the CEMP star HE 0338-3945 (Jonsell et al. 2006) showed that it is rich in both s- and r-elements. Jonsell et al. (2006) reported that this object locates near to the main sequence turnoff with metallicity of $[\text{Fe/H}] = -2.42$. They concluded that the observed heavy element abundances of HE 0338-3945 could not be well fit by a scaled solar r-process pattern nor by a scaled solar s-process pattern. It is a challenging problem to quantitatively understand of the origins of neutron-capture elements in the double-enhanced halo stars. Although some of the basic tools for this task were presented several years ago, the origins of the neutron-capture elements in the double-enhanced halo stars, especially r-process elements, are not clear, and the characteristics of the s-process nucleosynthesis in the AGB stars are not ascertained. Clearly, the study of element abundances in these objects is important for investigation of the origin of neutron-capture elements in these objects and in our Galaxy. One might hope that a clarification of the origin of r+s stars may shed some light on the general questions concerning the sites of r- and s-processes.

It is interesting to adopt the parametric model for metal-poor stars presented by Aoki et al. (2001) and developed by Zhang et al. (2006) to study the physical conditions that could reproduce the observed abundance pattern found in such type stars. In this paper, we investigate the characteristics of the nucleosynthesis pathway that produces the special abundance ratios of the r- and s-rich object HE 0338-3945 using the AGB parametric model. The calculated results are presented in Sect. 2, where we also discuss the characteristics of the s-process nucleosynthesis and the possible origin of their r-process elements. Conclusions are given in Sect. 3.

2.   Results and Discussion

By comparing the observed abundances pattern with the predicted s- and r-process contributions, we explore the origin of the heavy elements in HE 0338-3945. We adopt the parametric model for metal-poor stars presented by Zhang et al. (2006). The abundance of the ith element in the envelope of a star can be calculated as follows:

$$N_i(Z) = C_s N_{i,\ s} + C_r N_{i,\ r} 10^{[Fe/H]}, \tag{1}$$

where Z is the metallicity of the star, $N_{i,\ s}$ is the abundance of the ith element produced by the s-process in the AGB star and $N_{i,\ r}$ is the abundance of the ith element produced by the r-process (per Si $= 10^6$ at $Z = Z_\odot$), whereas, C_s and C_r are the component coefficients that correspond to contributions from the s-process and the r-process, respectively. The extremely metal-poor star CS 22892-052 merits special attention, because this star has an extremely large overabundance of neutron-capture elements relative to iron with [Fe/H] $= -3.1$. Many authors (Cowan et al. 1999; Sneden et al. 1996, 2000, 2003; Norris et al. 1997; Pfeiffer et al. 1997) suggested that the abundance patterns of the heavier ($Z \geq 56$) stable neutron-capture elements in very metal-poor stars are consistent with the solar system r-process abundance distribution, and this concordance breaks down for the lighter neutron-capture elements in the range of $40 < Z < 56$ (Sneden et al. 2000). Zhang et al. (2002) reported that when the abundances of the lighter elements in CS 22892-052 are multiplied by a factor of $1/0.4266$, the abundance distributions obtained for both heavier and lighter neutron-capture elements are in accordance with the solar system r-process pattern. This star could have abundances that well reflect the nucleosynthesis of a single supernova (Fields et al. 2002), so the adopted abundances of nuclei $N_{i,\ r}$ in equation (1) are taken as the solar system r-process abundances (Arlandini et al. 1999) for the elements heavier than Ba, and for the lighter nuclei we use solar system r-process abundances multiplied by a factor of 0.4266. There are four parameters in our model for r+s stars, such as the neutron exposure per thermal pulse $\Delta\tau$, the overlap factor r, the component coefficient of the s-process C_s, and the component coefficient of the r-process C_r. Using the observed data in the sample star HE 0338-3945 (Jonsell et al. 2006), the parameters in the model can be obtained from the parametric approach.

Our best-fit results are shown in figure 1. For HE 0338-3945, the curves produced by our model are consistent with the observed abundances for almost all the 21 heavy elements within the error limits. The good agreement between the model results and the observations provides strong support for the validity and reliability of the derived neutron-capture nucleosynthesis parameters. The overlap factor r is a fundamental parameter in the AGB model. At solar metallicity, Gallino et al. (1998) found that the value of the overlap factor r is between 0.4 and 0.7 in their standard evolution model for low-mass ($1.5 - 3.0 M_\odot$) AGB stars. The overlap factor deduced for HE 0338-3945 is $r = 0.40$, which lies in the above

range. The overlap factor for different initial-mass AGB stars as a function of metallicity has been presented by Cui & Zhang (2006) (see their Figure 1). Considering its metallicity, we suggest that the mass of the primary star (former AGB star) is less than $3.0 M_\odot$, i.e. it lies between 2.0 and $3.0 M_\odot$.

The neutron exposure per pulse $\Delta\tau$ is another fundamental parameter. Zhang et al. (2006) have deduced neutron exposures per pulse for other s-enhanced metal-poor stars, and found they lie between 0.45 and 0.88 mbarn^{-1}. The neutron exposure deduced for HE 0338-3945 is $\Delta\tau = 0.77$ mbarn^{-1}, which also lies in above range. In the case of multiple subsequent exposures, the mean neutron exposure is given by $\tau_0 = -\Delta\tau/\ln r$. We note that the value of $\tau_0 = 2.92(\frac{T_9}{0.348})^{1/2}$ mbarn^{-1} ($T_9 = 0.1$, in units of 10^9 K) for HE 0338-3945 is significantly greater than that of $\tau_0 = (0.30 \pm 0.01)(\frac{T_9}{0.348})^{1/2}$ mbarn^{-1}, which is best fit the solar system abundances (Käppeler et al. 1989). In fact, the higher mean neutron exposure favors the more amount of much heavier elements produced, such as Ba and Pb etc. For the s-only star CS 30322-023, Cui et al. (2007) obtained its mean neutron exposure, i.e. $\tau_0 = 2.38(\frac{T_9}{0.348})^{1/2}$ mbarn^{-1}, which is lower than that of HE 0338-3945. Based on the observation results (Jonsell et al. 2006; Masseron et al. 2006), we can find that the abundance ratios of [hs/ls] = 1.36 (where hs denotes the 'heavy' s-process elements, such as Ba, La, Ce and ls denotes the 'light' s-process elements, such as Sr, Y, Zr) in HE 0338-3945 is larger than that of [hs/ls] = 0.79 in CS 30322-023. This is consistent with the relation between the two mean neutron exposure for these two stars. [Pb/hs] is particularly useful in investigating the efficiency of the s-process site (Straniero et al. 2005). Using both the convective model and the radiative model, Cui & Zhang (2006) have calculated [Pb/hs] versus [Fe/H] for different initial stellar mass. Considering the [Pb/hs]= 0.82 and [Fe/H] = −2.42 for HE 0338-3945, we suggest that the mass of the former AGB star is about $2.5 M_\odot$.

For CEMP-s stars the most likely scenario is the pollution by mass transfer from a more massive AGB companion in a binary system, the later has undergone AGB nucleosynthesis and become a white dwarf. The s-process elements and C abundances in HE 0338-3945 are a result of pollution from the dredged-up material in the former AGB star. The measured [s/Fe] refers to the average s-process material in the AGB star after dilution by mixing with the envelope of the companion that is now the extrinsic star. Other parameters deduced for HE 0338-3945 are $C_s = 0.0050$ and $C_r = 61.0$. During the AGB evolution, the convective He shell and the envelope of the star are overabundant in heavy elements by factors f_{shell} and $f_{env, 1}$, respectively. The approximate relation between $f_{env, 1}$ and f_{shell} is

$$f_{env,\ 1} \approx \frac{\Delta M_{dr}}{M_1^e} f_{shell}, \tag{2}$$

where ΔM_{dr} is the total mass dredged up from the He shell into the envelope of the AGB star and M_1^e is the envelope mass of the AGB star. For a given s-process element, the

overabundance factor $f_{env,\ 2}$ in the extrinsic star's envelope can be approximately related to the overabundance factor $f_{env,\ 1}$ by

$$f_{env,\ 2} \approx \frac{\Delta M_2}{M_2^e} f_{env,\ 1} \approx \frac{\Delta M_2}{M_2^e} \frac{\Delta M_{dr}}{M_1^e} f_{shell}, \tag{3}$$

where ΔM_2 is the amount of matter accreted by the extrinsic star, M_2^e is the envelope mass of the star. The component coefficient C_s is computed from the relation

$$C_s = \frac{f_{env,\ 2}}{f_{shell}} \approx \frac{\Delta M_2}{M_2^e} \frac{\Delta M_{dr}}{M_1^e}. \tag{4}$$

It is found that substantial enhancements of carbon and nitrogen with respect to iron are common among CEMP stars (Cohen et al. 2003; Ivans et al. 2005; Jonsell et al. 2006). AGB nucleosynthesis models for low initial mass ($< 2.5 M_\odot$) show that carbon is produced by the 3α reaction during thermal pulses, but not nitrogen because it is burned during the same helium shell flashes, while for higher mass AGB stars the dredged-up carbon effectively converts into nitrogen by CN-cycling at the bottom of the convective envelope (hot bottom burning, HBB; Pols et al. 2008). Detailed evolution models of AGB stars (Karakas & Lattanzio 2007) showed that HBB sets in at significantly lower mass at low metallicity ($3.0 M_\odot$ at [Fe/H] $= -2.3$) than that at solar metallicity (around $5.0 M_\odot$). In figure 2, we show the enhancements of N and C relative to iron in HE 0338-3945 and compare them with the predicted abundance ratios for AGB models according to Karakas & Lattanzio (2007) with $Z = 0.0001$. The possible abundance ratios of the companion polluted by a former AGB star with different initial mass are plotted as solid lines. From this figure we can see that AGB stars with masses between 2.0 and $3.0 M_\odot$ produce nitrogen and carbon in the right amounts to account for the observed abundances, after accretion of the material by a low-mass companion and subsequent dilution in its envelope. For $2.5 M_\odot$, the factor $\frac{\Delta M_{dr}}{M_1^e}$ is about 1/6 (Karakas & Lattanzio 2007) and comparing the observation abundance of C and N with the calculated results of Karakas & Lattanzio (2007), the dilution factor $\frac{\Delta M_2}{M_2^e}$ for HE 0338-3945 is about 1/33 (see figure 2). The value of $C_s = 0.0051$ is deduced from equation (4), which is close to our calculated value, i.e. $C_s = 0.0050$, for HE 0338-3945 using the parametric model. As the observational abundance ratios of [C/Fe] $= 2.13 \pm 0.15$ and [N/Fe] $= 1.55 \pm 0.17$ (Jonsell et al. 2006), we believe that HBB does not happen in the AGB companion, i.e. the initial mass of the AGB companion is less than $3.0 M_\odot$ (Karakas & Lattanzio 2007) with its metallicity considered, which is in agreement with the obtained results. It should be mentioned that the C and N abundances come from the Jonsell et al. (2006) 1D LTE analysis based on the CH and CN molecule lines, however, which are uncertain, due to the strong temperature sensitivity of the CH and CN molecule formation. Preliminary results for the 3D corrections may amount to approximately -0.5 to -0.3 and -0.5 dex for carbon and

nitrogen, respectively (Asplund & Garcia Pérez 2001; Asplund 2004; Jonsell et al. 2006). The results, when the 3D corrections of -0.5 dex for carbon and nitrogen are considered, are also shown in figure 2. We can see form this figure that the 3D effects do not influence our results.

Zijlstra (2004) suggested that the strong metallicity dependence of mass loss during the AGB phase leads to a steeper initial-final mass relation for low-metalliciy stars, that is, for a given initial mass, the final mass is higher for metal-poor stars. Therefore, the core of, e.g., a metal-poor star with [Fe/H] $= -3.0$ having an initial mass of $4.0 M_\odot$ would reach the Chandrasekhar mass, leading to a "Type 1.5" supernova. In such a supernova, r-process nucleosynthesis might occur, and the surface of the companion star observed today could have been polluted. Our results imply clearly that HE 0338-3945 should be polluted by a $2.5 M_\odot$ AGB star, which could not cause a "Type 1.5" supernova. The component coefficient of the r-process calculated for HE 0338-3945 is $C_r = 61.0$, which means that this star and its AGB companion should form in a molecular cloud that had already been polluted by r-process material.

Apart from carbon and nitrogen, we concentrate on oxygen enrichments as possible tracers of the origin of CEMP stars. Jonsell et al. (2006) derived a super-solar oxygen abundance of [O/Fe] $= +1.40$ in the halo star HE 0338-3945. In figure 3, we show the enhancements of O and C relative to iron observed in HE 0338-3945 and compare these to the abundance ratios in the material lost by AGB stars with [Fe/H] $= -2.3$ according to the Karakas & Lattanzio (2007). The abundance ratios of the companion polluted by a former AGB star with different initial mass are plotted as solid lines. This figure shows that AGB stars with masses between 1.25 and $6.0 M_\odot$ do not produce enough O to account for the observed abundance. This means that O doesn't mainly come from the former AGB star, it must have another origin. It is noteworthy that the O abundance derived by Jonsell et al. (2006) based on 1D LTE analysis of the O I triple lines, which are known to be sensitive to the NLTE effects. Jonsell et al. (2006) estimated the NLTE effects were to be ~ -0.1 dex. However, recently, Fabbian et al. (2009) have redone the O I NLTE calculations with new electron collisional data, which leads to much larger NLTE effects, about -0.3 to -0.6 dex for the given stellar parameters. However, the exact corrections depend on the still uncertain hydrogen collisional cross-sections. For this star, we estimate that the NLTE correction of O is of the order of -0.5 dex, and the result is also shown in figure 3. From this figure, we can see that the O abundance in HE 0338-3945 is still not reproduced by the AGB model, even if the NLTE corrections have been considered.

The observed results for HE 0338-3945 (Jonsell et al. 2006) are shown as filled circles in figure 4, where the red solid line represents the results calculated by the parametric model,

while the black solid line represents the results given by Karakas & Lattanzio (2007) for $2.5M_\odot$ AGB model adopting a factor $\frac{\Delta M_2}{M_2^e}$ of 1/33. It can be seen that there is good agreement between the observation data on C, N and these of the AGB model within the error limits. It is interesting to simultaneously analyse the observed light and heavy elements to study the physical conditions that could reproduce the observed abundance pattern found in this star. Indeed, some very metal-poor stars, such as CS 22892-052, have high abundance ratios of heavier neutron-capture elements, e.g. Eu (Sneden et al. 2003). CS 22892-052 possibly record the abundance patterns produced by the r-process and is called as an r-II star. In this star, the abundances of neutron-capture elements are in remarkable agreement with the scaled solar system r-process pattern (Sneden et al. 2003). This is the first determination of the overall abundance pattern that could represent the yields of the r-process. The abundances in this star must have been printed and enhanced by the r-process elements and other elements which are produced in conjunction with the r-process. In order to investigate the light elements pattern in this r+s star, we use CS 22892-052 as an r-process only star, and plot its observed element abundances normalized to Eu in this figure, too (see the blue dash dot line; Sneden et al. 2003). It is believed that Eu is mainly made by the r-process. For the two stars, HE 0338-3945 and CS 22892-052, shown in this figure, have almost identical abundance pattern from N to Cu including O, but the C and heavy s-process elements, such as Ba and Pb, differ greater than 0.8 dex, which indicates that the origin of C and s-process elements is AGB stars. Because the overabundance of O and C for HE 0338-3945, could not be explained simultaneously by any AGB star (see figure 3), we can conclude that the production of O should accompany with the production of the heavy r-process elements for this r+s star. We note that though the overabundance of O for HE 0338-3945 is larger than that for CS 22892-052, but when considering its also larger overabundance of Eu, the abundance pattern of O and r-process elements for HE 0338-3945 is still close to that for the r-II star CS 22892-052. It can be found that the heavy r-process elements are not produced in conjunction with all the elements from Na to Fe group elements, which is similar to r-II stars, too (Qian & Wasserburg 2007). Combined the calculated results of neutron-capture elements, we find that the abundance pattern of the r-process and light elements in HE 0338-3945 is vary close to that of the r-II star CS 22892-052. This implies that this star should be a special r-II star? In this figure, we do not attempt to correct the C, N and O abundance in HE 0338-3945 for 3D or NLTE effects quantitatively because of the still uncertain H collisions. Although the corrections are expected to decrease their abundances, our conclusions are not significantly influenced.

It is important to discuss the uncertainty of the derived parameters using the method presented by Aoki et al. (2001). Figures 5 and 6 show the calculated ratios $\log\varepsilon(\mathrm{Sr})$, $\log\varepsilon(\mathrm{Ba})$, $\log\varepsilon(\mathrm{Pb})$ and $\log\varepsilon(\mathrm{Eu})$ as a function of the neutron exposure $\Delta\tau$ in a model with $r = 0.40$

and as a function of overlap factor r with a fixed neutron exposure $\Delta\tau = 0.77$ mbarn^{-1}. These are compared with the observed abundance ratios in HE 0338-3945. There is only a region of overlap in figure 5, $\Delta\tau = 0.77^{+0.01}_{-0.04}$ mbarn^{-1}, in which all the observed ratios referred above can be accounted for. The bottom panel in figure 5 displays the reduced χ^2 value calculated in our model, and there is a minimum $\chi^2 = 1.008$ at $\Delta\tau = 0.77$ mbarn^{-1}; the neutron exposure is constrained quite well. The abundance ratios $\log\varepsilon(\text{Sr})$, $\log\varepsilon(\text{Ba})$, $\log\varepsilon(\text{Pb})$ and $\log\varepsilon(\text{Eu})$ are insensitive to the overlap factor r and allow for a wider range, i.e. $0.3 < r < 0.42$.

3. Conclusions

The chemical abundances of the extremely r- and s-rich star HE 0338-3945 are an excellent test bed to set new constraints on models of neutron-capture process nucleosynthesis at low metallicity. The neutron-capture element abundance pattern of HE 0338-3945 could be explained by a binary system formed in a molecular cloud that had ever been polluted by r-process material. Based on the good fit using the AGB models (Karakas & Lattanzio 2007) and parametric model (Zhang et al. 2006) to match the observed abundance pattern including the abundances of C and N, we deduce that the progenitor mass of the AGB star is about $2.5M_\odot$. The more massive companion underwent an AGB phase, and produced lots of C, N and s-process isotopes. Subsequently, the envelope of HE 0338-3945 is enriched with the dredged-up material from the former AGB star. The initial mass of the AGB companion is less than $4.0M_\odot$, which excludes the possibility of forming a Type 1.5 supernova. Overall, the predicted abundances for the r/s-process fit well the observed abundance patterns of HE 338-3945, for the first (Sr and Zr) and second peaks (Ba and La), as well as the third peak of the s-process (Pb). We find that the production of O should accompany with the production of the heavy r-process elements for r+s stars and the contribution of O in HE 0338-3945 from the AGB stars is swamped by the pre-enrichment of O. Similar to r-II stars, the heavy r-process elements are not produced in conjunction with all the elements from Na to Fe group elements. The abundance pattern of the r-process and light elements in HE 0338-3945 is very close to that of the r-II star CS 22892-052. This implies that this star may be a special r-II star.

Clearly, it is important for future studies to determine the relation between r-II and r+s stars, whether the r-pattern in r-II stars can explain the abundance distribution of the r-material in r+s stars. More in-depth theoretical and observational studies of r-rich and r+s stars will reveal the characteristics of the r- and s-process at low metallicity and the history of the enrichment of neutron-capture elements in the early Galaxy.

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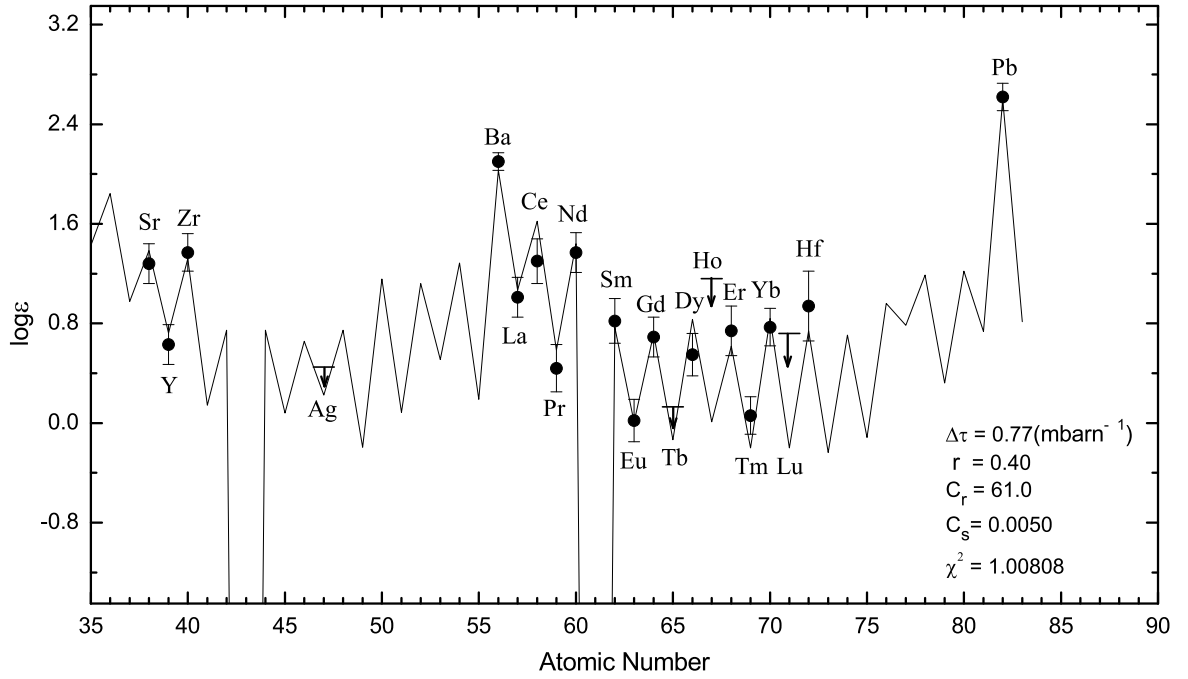
Fig. 1.— Best fit to observational results of metal-deficient star HE 0338-3945. The filled circles with appropriate error bars and downward arrows denote the observed element abundances, the solid lines represent predictions from s-process calculations, in which the r-process contribution is considered simultaneously. The standard unit of $\Delta\tau$ is mbarn^{-1}.
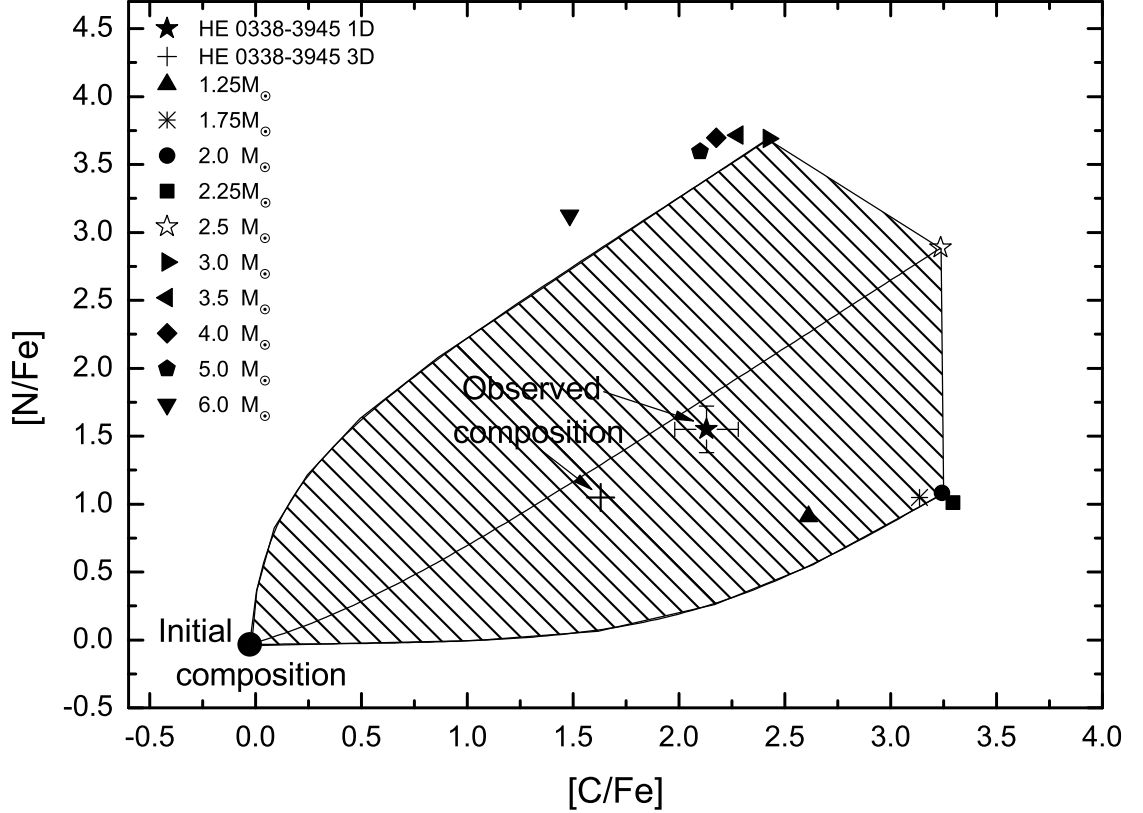
Fig. 2.— Abundance ratios of N and C with respect to Fe as observed in HE 0338-3945 with appropriate error bars (filled asterisk, taken from Jonsell et al. 2006), and predicted by Karakas & Lattanzio (2007) AGB stars at $[Fe/H] = -2.3$, with labels indicating the initial masses. The cross represents the abundance ratios which have been corrected by 3D effects. The initial composition is scaled from solar. The hatched ellipsoid is the region of the plot where the N and C abundances from the AGB companion should lie to ensure that the observed abundances are reproduced after dilution. The unfilled asterisk represents possible former AGB star with initial mass $2.5 M_\odot$ computed by Karakas & Lattanzio (2007) models.
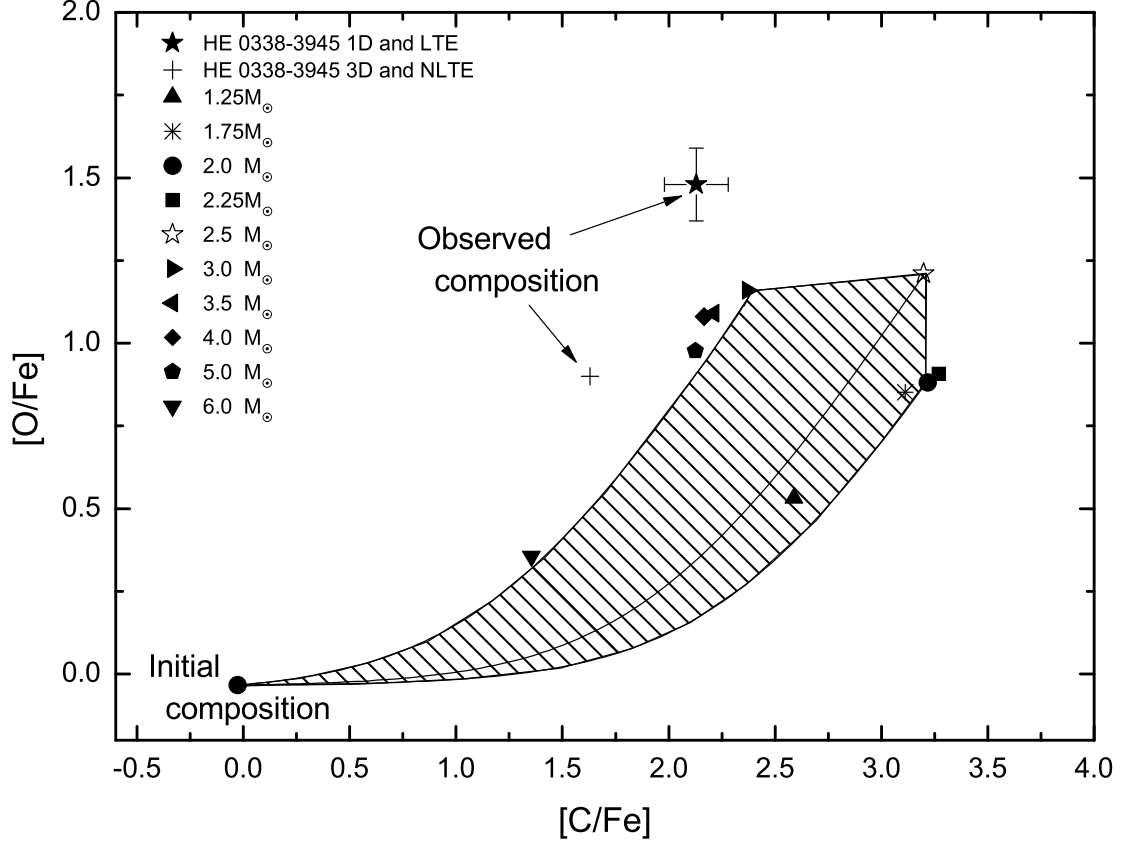
Fig. 3.— Abundance ratios of O and C with respect to Fe as observed in HE 0338-3945 with appropriate error bars (filled asterisk, taken from Jonsell et al. 2006), and predicted by Karakas & Lattanzio (2007) AGB stars at [Fe/H] = −2.3, with labels indicating the initial masses. The cross represents the abundance ratios which have considered the NLTE effects for O and 3D effects for C, respectively. The initial composition is scaled from solar. The hatched ellipsoid is the region of the plot where the observed abundances of O and C can be reproduced by the abundances after dilution from the AGB companion predicted by Karakas & Lattanzio (2007) models.
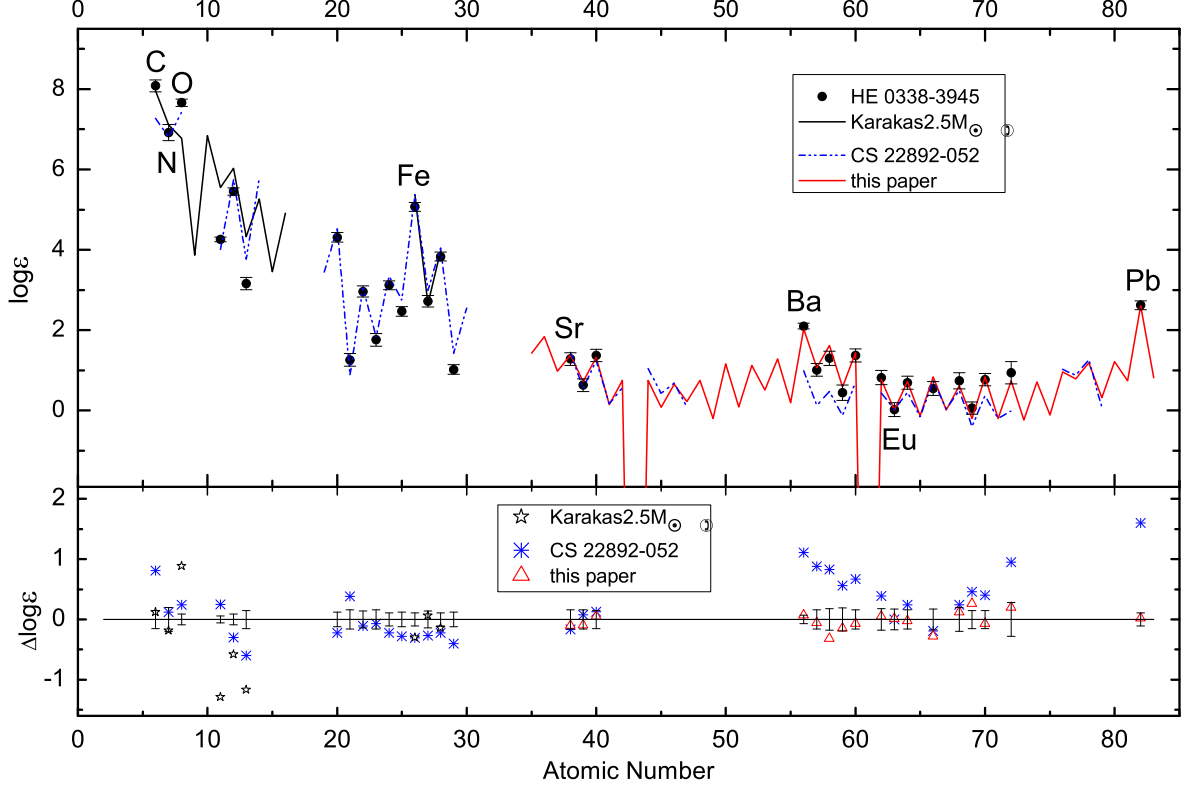
Fig. 4.— The abundance pattern of HE 0338-3945 (filled circles and downward arrows) compare with predictions from s-process calculations of parametric AGB model with r-process contribution considered (red solid line), predictions from Karakas & Lattanzio (2007) $2.5 M_\odot$ star model with [Fe/H] $= -2.3$ (black solid line), and the abundance pattern of a r-II star CS 22892-052 (adopted from Sneden et al. 2003) scaled to the Eu abundance of HE 0338-3945 (blue dash dot line). The estimated absolute error bars are shown. The bottom panel displays the difference, defined as $\Delta \log \varepsilon(\mathrm{X}) \equiv \log \varepsilon(\mathrm{X})_{obs} - \log \varepsilon(\mathrm{X})_{calc}$, and upper limits are not shown. Note that none of the displayed C, N and O abundances have been corrected for 3D or NLTE effects.
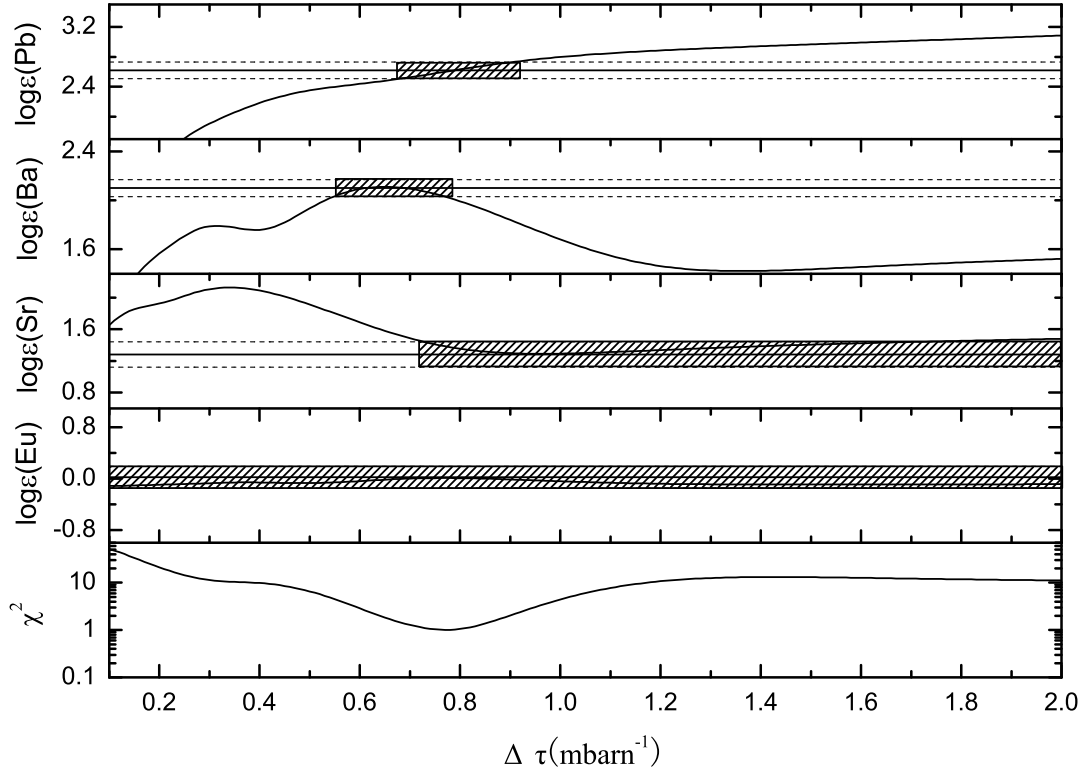
Fig. 5.— Logarithm abundances $\log\varepsilon$(Pb), $\log\varepsilon$(Ba), $\log\varepsilon$(Sr) and $\log\varepsilon$(Eu) in r+s star HE 0338-3945, and reduced χ^2 (bottom) as a function of the neutron exposure $\Delta\tau$ computed by a model with $C_r = 61.0$, $C_s = 0.0050$ and $r = 0.40$. These are compared with the observed abundances of HE 0338-3945 adopted from Jonsell et al. (2006).
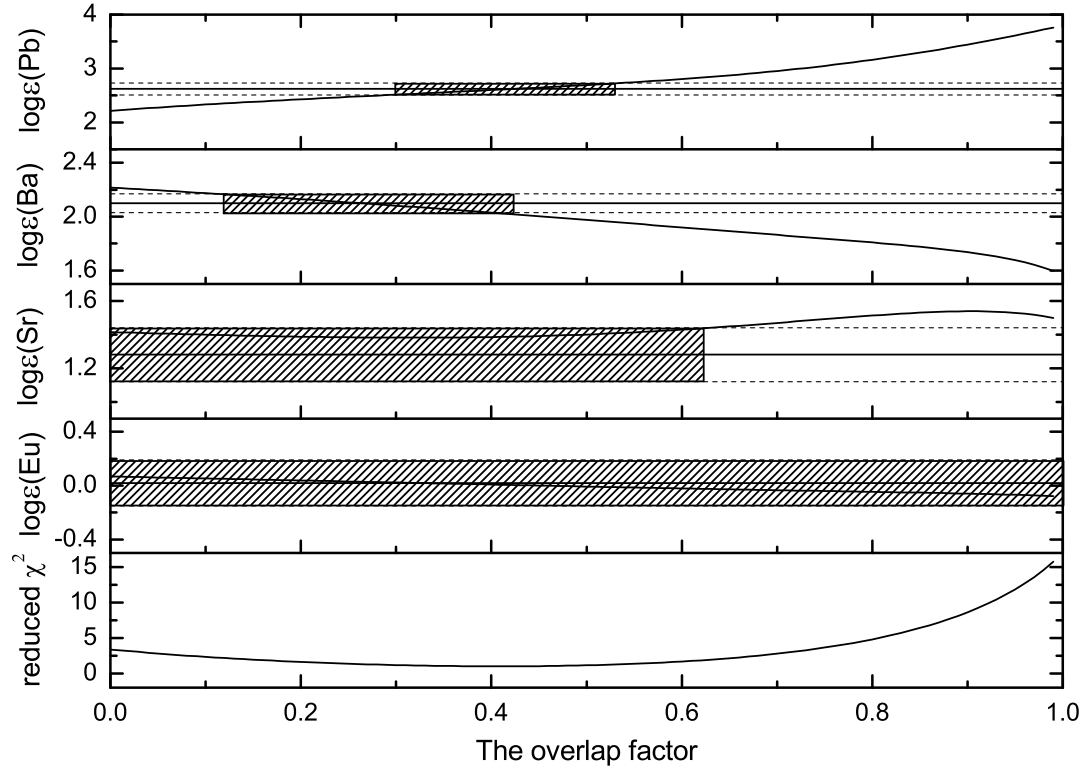
Fig. 6.— Same as those in Fig. 5 but as a function of the overlap factor r in a model with $\Delta\tau = 0.77$ mbarn^{-1}.